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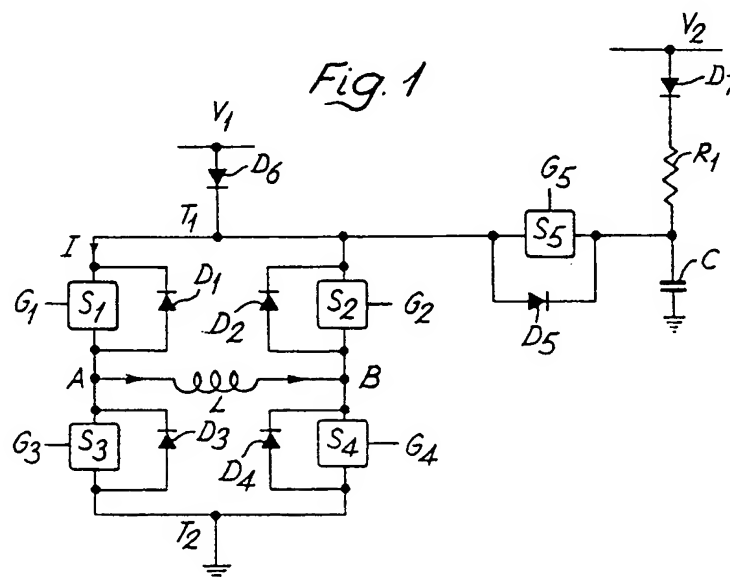H03K 17/64  H02M 7/538  H03K 17/687

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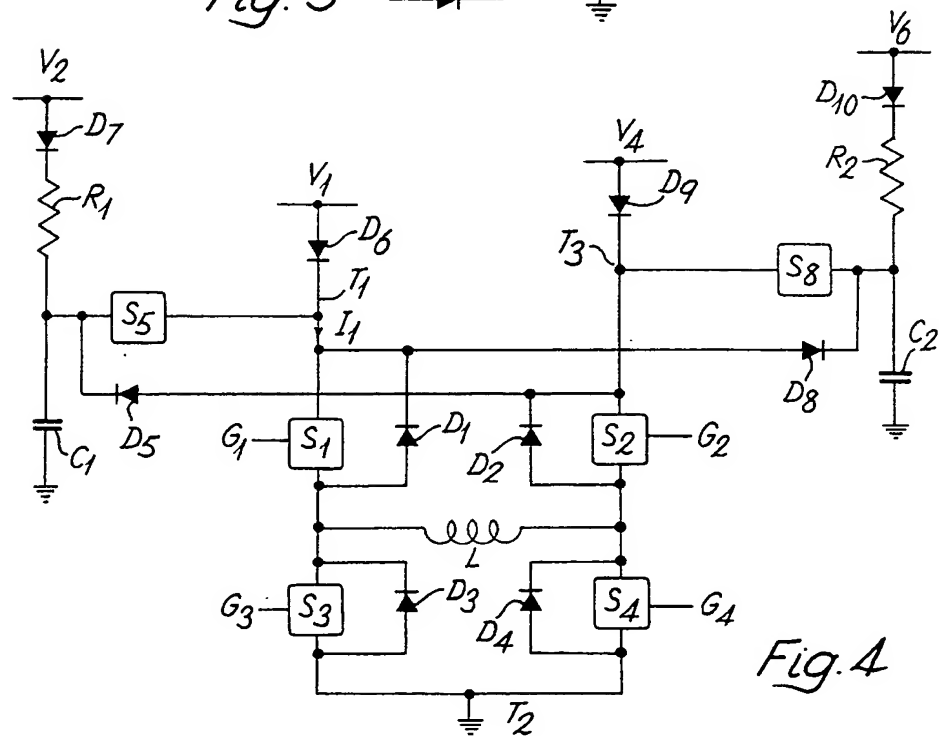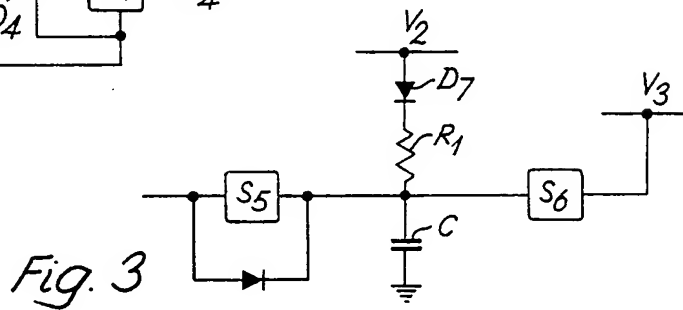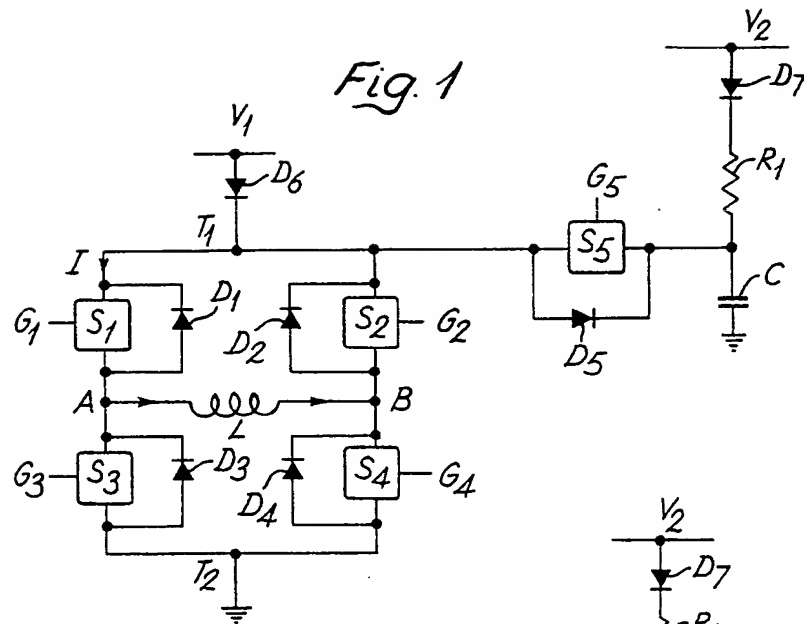U1S 2137 H3T

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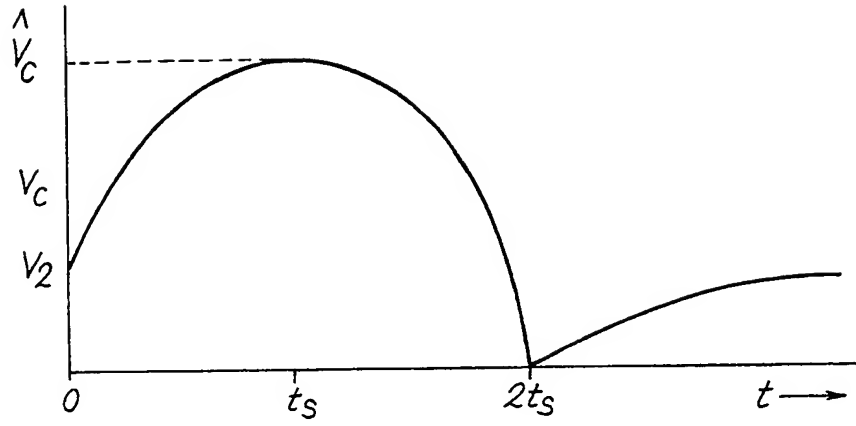H02P H03K

(54) Inductive circuit arrangements

(57) A switched coil arrangement is connected in a bridge configuration of four switches $S_1$, $S_2$, $S_3$ and $S_4$ which are each shunted by diodes $D_1$, $D_2$, $D_3$ and $D_4$ so that current can flow in either direction through a coil L depending on the setting of the switches. A capacitor C is connected across the bridge through a switch $S_5$ to receive the inductive energy stored in coil L on breaking the current flow path through the coil. The electrostatic energy stored in capacitor C can then be used to supply current through the coil in the reverse direction either immediately or after a time delay. Coil L may be a superconductive coil. Losses in the circuit can be made up by a trickle charge of capacitor C from a separate supply $V_2$. The device may be used in nuclear magnetic resonance imaging.
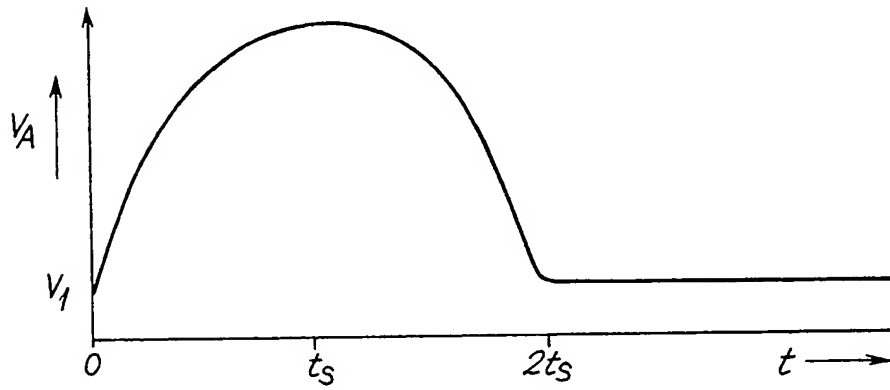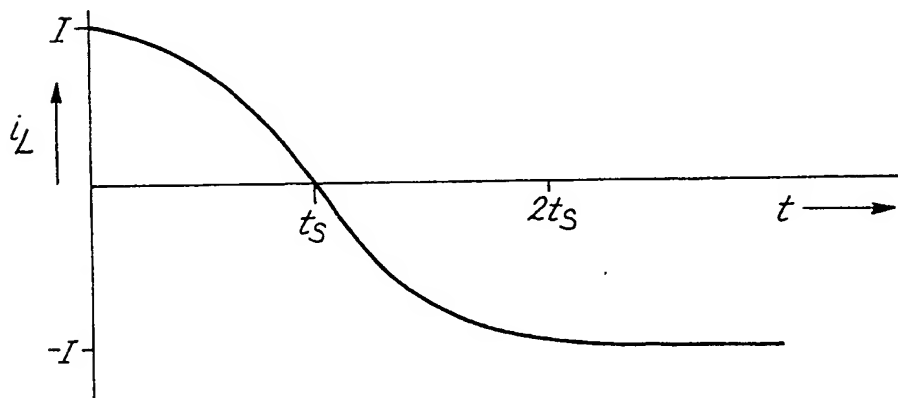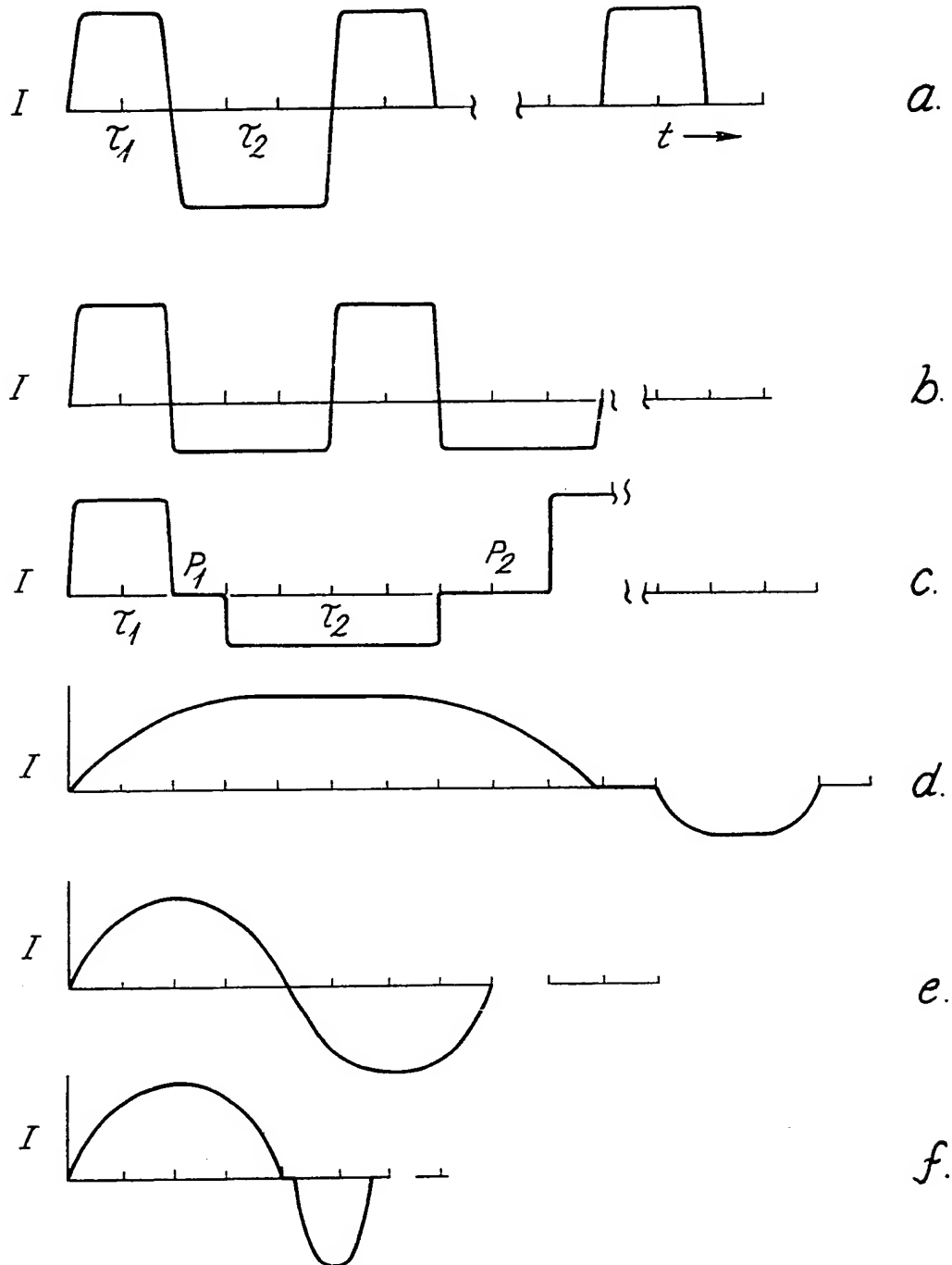


Fig. 1

Fig. 1



Fig. 3



Fig. 4

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$$\hat{V_C}$$

$V_C$

$V_2$

$0 \qquad t_S \qquad 2t_S \qquad t \longrightarrow$

a.

$V_A$

$V_1$

$0 \qquad t_S \qquad 2t_S \qquad t \longrightarrow$

b.

$I$

$i_L$

$t_S \qquad 2t_S \qquad t \longrightarrow$

$-I$

c.

Fig. 2

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3/5



a.

b.

c.

d.

e.

f.

Fig. 5

Fig. 6

Fig. 7

+ SUPPLY (12V)

$D_3$

$G_1$ $S_1$

$S_2$ $G_2$

$S_5$ $G_5$

$L = 100\mu H$

$i$

$27\Omega$

$10\mu F$

$G_3$ $S_3$

$S_4$ $G_4$

0-60V
TOP UP
SUPPLY
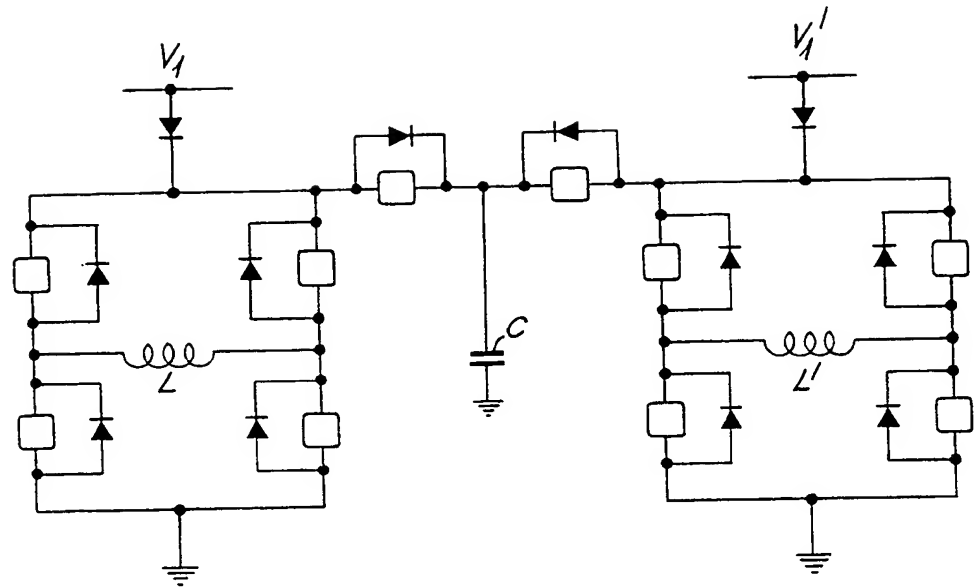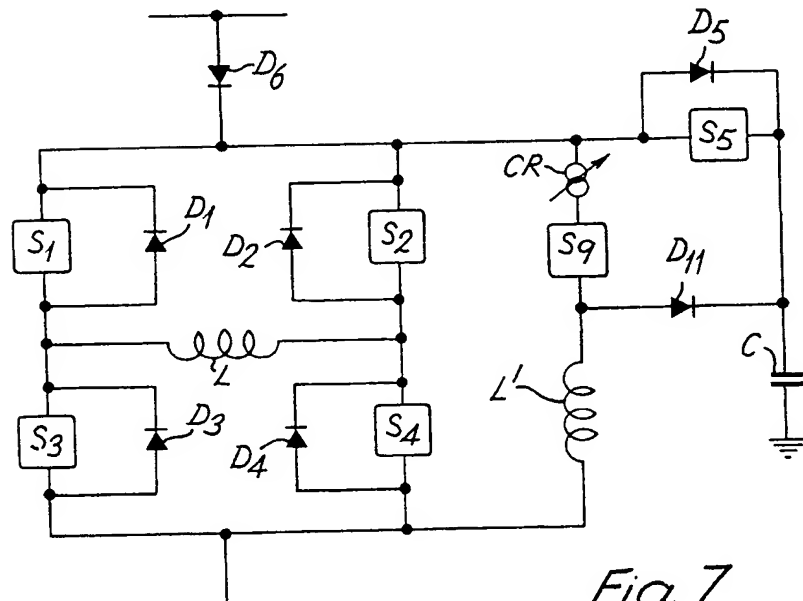
− SUPPLY

Fig. 8

## SPECIFICATION
## Inductive circuit arrangements

This invention relates to inductive circuit
5 arrangements and is concerned with arrangements
which enable the current flow through an inductive
coil to be rapidly switched on and off or reversed.

In many applications of nuclear magnetic
resonance (NMR) it is often required to switch on or
10 off or to reverse magnetic fields and especially
magnetic gradient fields and to effect such
switching or reversal as rapidly as possible.
Switching of magnetic gradient fields is important in
NMR imaging applications especially where high
15 speed is required. An example of such an
application is in the echo planar imaging (EPI)
technique as described in British Patent
No. 1,596,160. In EPI there is a requirement to switch
trapezoidal gradient fields with a switching time of
20 around 25 μs for best effect. These gradient fields
are created by passing electrical currents through
inductive coil arrangements which may have non-
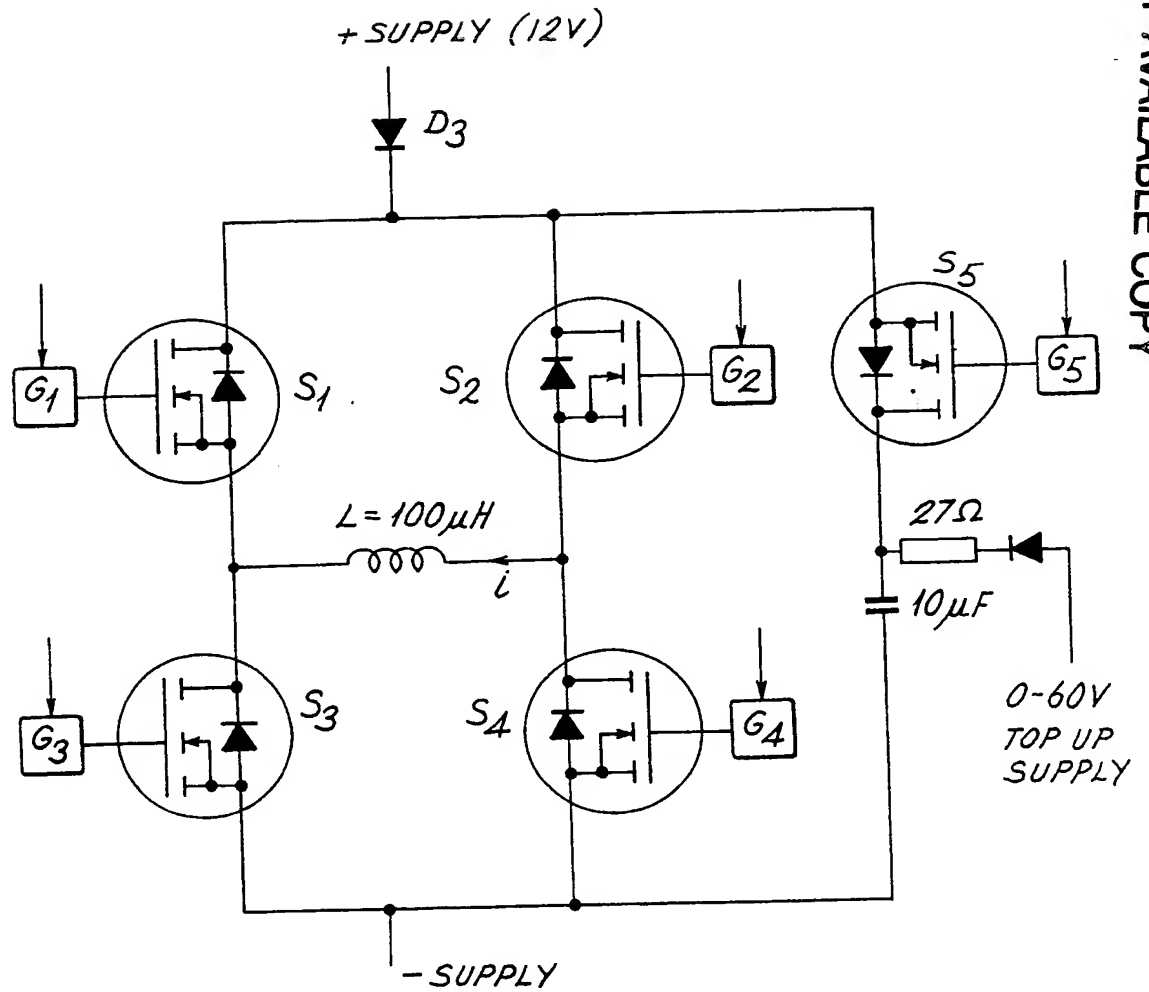zero resistance. For low resolution imaging low
currents and small coil assemblies can be utilised
25 and it is possible to use linear amplifiers to achieve
the required switching rates and gradient
amplitudes. However if high resolution is required
larger gradient fields must be employed and to
achieve the required high switching rates extremely
30 high power amplifiers are necessary. It is believed
that this is one of the major obstacles to the
commercial development of ultra high-speed NMR
imaging techniques like EPI.

The power requirements for the rapid switching of
35 current through an inductance will be appreciated
from a consideration of the theoretical background.
Let a step voltage V be applied to an inductance L
through a resistor r then the size of current i is given
by the well known expression
40

$$i = I(1 - e^{-t/\tau}) \qquad (1)$$

in which

45
$$I = V/r \qquad (2)$$

and the time constant τ is given by

$$\tau = L/r. \qquad (3)$$
50

The magnetic energy E contained in the coil at any
time t is given by

$$E = \tfrac{1}{2}Li^2 \qquad (4)$$

55
The peak power $P_L$ required to establish this energy
in the coil is

60
$$P_L = \frac{dE}{dt} = (LI^2/\tau)e^{-t/\tau}(1 - e^{-t/\tau}). \qquad (5)$$

The steady-state power dissipation $P_r$ in the coil is
simply
65

$$P_r = I^2 r. \qquad (6)$$

For very low winding resistance, this power can be
made arbitrarily low. However, for a given value of
70 inductance L and rise time, equation (5) determines
the peak power requirements of the driver amplifier.
For linear amplifiers this situation presents
something of a dilemma. Peak powers and voltages
exceeding the capability of the amplifier may be
75 required for short durations only, in order to
establish the steady state current I. Then according
to equation (6), the power requirement may drop to
an arbitrarily low figure, though I may be high.

Linear amplifiers with both high voltage and high
80 current capability are not readily available but in any
event are an inefficient and uneconomic approach
for gradient switching.

For superconductive coils, r = 0 so that τ → ∞,
equation (3). In this case, it would take an infinite
85 time (in practice a long time) to establish any current
through L. But having established a current, no
power would be required to maintain it.

It is an object of the invention to provide an
inductive circuit arrangement the switching of
90 which requires minimal power.

According to the invention an inductive circuit
arrangement comprises four switches connected in
a bridge configuration, current supply terminals to
opposite ends of the bridge, inductive coil means
95 connected across the bridge so that current can flow
in either direction through the coil means
depending on the setting of the switches, a series
connection of capacitor means and a switch
connected across the supply terminals, and means
100 for operating the said switches so as to connect the
capacitor means across the coil means at least for a
sufficient period of time until the current flow
through the coil reduces to zero by charging of the
capacitor means.

105 In carrying out the invention the said means for
operating the switches may function subsequently
to allow the capacitor means to discharge to
generate current flow through the coil means in the
opposite direction to the initial flow.

110 Preferably the said switches are shunted by
unidirectional current flow devices.

It will be seen that in the operation of the above
circuit arrangement the magnetic energy stored in
the inductive coil is not destroyed but is
115 transformed to electrostatic energy for storage in
the capacitor means. Thus the power required to
switch or reverse the current through the coil is
theoretically zero since the total energy of the
system comprising coil and capacitor is constant. In
120 practice there will be minor energy losses but these
can be compensated for by provided trickle charge
means connected to the capacitor means to enable
the capacitor means to be charged to a
predetermined voltage value after discharge. It is
125 desirable to ensure that the said predetermined
voltage is greater than the voltage across the supply
terminals.

It may be desirable to connect a unidirectional
current flow device in series with the current supply
130 terminals to prevent flow of current through the

current supply terminals in the reverse direction.

The invention is applicable both to circuit arrangements incorporating coils having finite resistance and to circuit arrangements
5 incorporating superconductive coils, in which case it may not be necessary to provide a potential difference across the supply terminals.

To provide start-up energy for the circuit initiating charge means can be connected through a switch to
10 initially charge the capacitor means to a peak voltage to provide the requisite electrical energy to establish the required current flow in the said coil means.

It may also be desirable to provide a switched
15 parallel path across the bridge to maintain a substantially constant value of current through the current supply terminals irrespective of the settings of the switches in the bridge configuration.

In one embodiment of the invention the bridge
20 configuration is so modified that the two arms of the bridge are connected to different current supply terminals and separate series connections each of a capacitor means and a switch are connected to each supply terminal so as to enable different values of
25 current flow to be established through the coil in respective opposite directions.

In certain embodiments of the invention the capacitor means is used as a temporary energy store only and a second inductive coil means is
30 provided as a more long-term store. Such an arrangement is useful where immediate current reversal in an operating coil is not required. In one such embodiment a further bridge configuration with associated further current supply terminals is
35 provided with a further inductive coil means connected across the said further bridge configuration and the capacitor means is also connected in series with a further switch across the further current supply terminals. With such an
40 arrangement the energy in the operating coil is first transferred to the capacitor means in the manner described above and is then transferred to the further inductive coil means where it can be stored indefinitely, with any losses if need be being made
45 up from the voltage source connected across the further current supply terminals.

In order that the invention may be more fully understood reference will now be made to the accompanying drawings in which:—
50 Figure 1 is a circuit arrangement embodying the invention,

Figure 2 shows waveforms explanatory of Figure 1,

Figure 3 illustrates a modification for Figure 1,
55 Figure 4 is a circuit embodying the invention for enabling opposite current flows in a coil to have different amplitudes,

Figure 5 illustrates various current waveforms possible by using the invention,
60 Figure 6 illustrates an embodiment of the invention in which two inductive coils are used,

Figure 7 illustrates another embodiment of the invention in which a second coil is used for energy storage, and
65 Figure 8 is an embodiment of the invention

utilising solid state switches.

Referring now to Figure 1 there is illustrated therein a bridge configuration of four switches $S_1$, $S_2$, $S_3$ and $S_4$. Each switch is shunted by a respective
70 diode $D_1$, $D_2$, $D_3$ or $D_4$. All the diodes are conductive in the same direction. An inductive coil L is connected across the bridge between points A and B. The bridge has current supply terminals $T_1$ and $T_2$, terminal $T_2$ being earthed and terminal $T_1$ being
75 supplied from a voltage or current supply $V_1$ through a diode $D_6$. A series connection of a capacitor C and switch $S_5$ is connected across the bridge between terminals $T_1$ and $T_2$ and switch $S_5$ is shunted by a diode $D_5$. Capacitor C can be charged
80 from a voltage supply $V_2$ through a diode $D_7$ and resistor $R_1$. The various switches $S_1$ to $S_5$ are controlled by signals applied along lines $G_1$ to $G_5$ respectively.

To understand the operation of the circuit shown
85 in Figure 1 let it be assumed initially that switches $S_1$ and $S_4$ are closed and that switches $S_2$ and $S_3$ are open. With this arrangement of the switches current will flow through coil L from terminal A to terminal B. If now at a time $t = 0$ switches $S_1$ and $S_4$ are
90 switched off simultaneously the magnetic field in coil L will collapse and will generate an emf across the coil and by Lenz's law point A will be negative with respect to point B. Point A is clamped to earth terminal $T_2$ through diode $D_3$ and since point B is
95 therefore positive there will be a continuous path for the current flowing in coil L through diodes $D_2$ and $D_3$, diode $D_5$ and capacitor C. The energy in coil L will therefore be dumped into capacitor C where it will be stored as electrostatic energy. While this
100 charging of capacitor C takes place switches $S_2$ and $S_3$ can be closed but the timing of their closure is not critical since current is flowing during this time through diodes $D_2$ and $D_3$. Switch $S_5$ is also closed during this time without affecting the operation of
105 the circuit. The current through coil L reaches zero at a time $t = t_s$ at which instant capacitor C becomes fully charged to a peak value of voltage $\hat{V}_c$. The time $t_s$ is defined by

110
$$t_s = \tfrac{1}{2}\pi\sqrt{LC} \qquad (7)$$

The current flow will reverse through the now closed switches $S_2$, $S_3$ and $S_5$ and capacitor C will entirely discharge to generate a current flow of
115 magnitude-I from B to A in the reverse direction through coil L after a time $2t_s$.

Neglecting the forward diode resistance, the total energy initially in the inductor at time $t = 0$ is transferred to the capacitor, i.e.
120
$$\tfrac{1}{2}LI^2 = \tfrac{1}{2}C\hat{V}_c^2 \qquad (8)$$

where $\hat{V}_c$ is the peak voltage appearing on C. Since L and C form a tuned circuit with frequency f is given
125 by

$$2\pi f = 1/\sqrt{LC} = 2\pi/4t_s \qquad (9)$$

the energy transfer time or switching time, $t_s$, can be
130 chosen by an appropriate value of C. The capacitor

voltage $V_c$ during a switch, is shown in Figure 2(a).
At $t = 0$, $V_c = V_2$. After energy transfer at $t = t_s$,
$V_c = \hat{V}_c$. Capacitor C discharges in the next $\frac{1}{4}$-cycle
through closed switch $S_5$. The discharge path is
5 through switches $S_2$ and $S_3$ thereby establishing a
reversed current, $-I$, through coil L. At the end of the
discharge period, when $t = 2t_s$, $V_c \simeq 0$ and at this
point in time switch $S_5$ is opened isolating C from
the circuit. Thereafter the capacitor is trickle charged
10 through resistor $R_1$ until $V_c = V_2$.

The voltage $V_A$ across the terminals $T_1$ and $T_2$ and
the current $i_L$ through coil L are shown in Figure 2(b)
and Figure 2(c) respectively. Prior to reversal,
$V_A \simeq V_1$ and $i_L = I$. At time $t = t_s$, $i_L = 0$ and $V_A = \hat{V}_c$.
15 The diode $D_6$ protects the low voltage power supply
during the switching operation and allows a smooth
transition back to $V_1$ following current reversal.
Since $D_1$ conducts when $S_1$ is switched off, a smooth
transition from I to $-I$ obtains, with no
20 discontinuous glitches at the zero-crossing.

The voltage $V_2$ is variable and serves to make
good energy losses in the system due to finite diode
and switch resistances.

As described the switch works with
25 superconductive coils.

The operation of the circuit of Figure 1 assumed
an initial steady state current flowing in the coil.
However, from Figure 2 it can be seen that at time
$t = t_s$, $i_L = 0$. That is to say, the circuit is switched
30 off. The conditions to switch on from $i_L = 0$ are
therefore those indicated, namely $V_c = \hat{V}_c$. In order
to achieve this, the circuit as it stands must be
cycled prior to actual operation to establish the
correct working voltages. However, capacitor C will
35 not hold its charge indefinitely and $V_c$ will slowly
decay from $\hat{V}_c$ to $V_1$ due to leakage resistance.
Typical leakages allow $V_c$ to be held for up to 100 ms
without problem.

To avoid droop, the circuit of Figure 1 must be
40 modified to take an additional power supply capable
of supplying the full peak voltage, i.e. $V_3 = V_c$. This
modification is sketched in Figure 3, in which a
voltage $V_3$ is connected to C via a switch $S_6$. This is
kept on when all other switches are off, that is,
45 between pulse sequences. As soon as current is
required through coil L, $S_6$ is switched off and the
bridge is activated. Once current is established, the
operations continue as previously described. On
final switch off, $V_3$ is again coupled to capacitor C via
50 switch $S_6$.

The fact that $S_1$ to $S_4$ are initially all off means that
the load on supply $V_1$ changes and voltage $V_A$
varies. This may be obviated by adding a third arm
to the bridge of Figure 1. This comprises a switched
55 load connected between terminal $T_1$ and earth
which is normally off. However, when no current
through coil L is required, the third arm shunts
current through diode $D_6$ to earth thereby holding
$V_A$ constant.
60 In the Figure 1 circuit the bridge configuration is
shown as comprising four switches. Two of these
switches, for example switches $S_2$ and $S_4$, may be
replaced by pairs of terminals for connection to
individual current supply sources which replace
65 source $V_1$. A duplicate of capacitor C and its

associated switch $S_5$ and bypass diode $D_5$ is
connected to the opposite end of the bridge to
switch $S_5$ and point A or B is earthed instead of
terminal $T_2$. Diodes are also included at each end of
70 the bridge.

In the circuit described in Figure 1 the magnitude
of the forward and reverse currents are equal.
However, in some NMR applications, unequal
magnitudes of current are required. The basic
75 principles of switching described above can be
adapted to this situation as indicated in Figure 4.

In the circuit shown in Figure 4 like parts have like
references to Figure 1 but in Figure 4 the two arms
of the bridge comprising the switches $S_1$ and $S_2$ are
80 taken to two different current supply terminals $T_1$
and $T_3$ supplied from voltage sources $V_1$ and $V_4$ of
different magnitudes. Separate capacitors $C_1$ and $C_2$
are connected to terminals $T_1$ and $T_3$ through
switches $S_5$ and $S_8$ respectively. Terminal $T_1$ is
85 connected to capacitor $C_2$ through a diode $D_8$ and
terminal $T_3$ is connected to capacitor $C_1$ through a
diode $D_5$ shunted by diodes $D_5$ and $D_8$. Capacitor $C_1$
is trickle charged from a voltage source $V_2$ through a
protective diode $D_7$ and resistor $R_1$. Capacitor $C_2$ is
90 trickle charged from a voltage source $V_6$ through a
protective diode $D_{10}$ and resistor $R_2$.

Let an initial current $I_1$ flow through switch $S_1$, coil
L and switch $S_4$. On turn-off of switches $S_1$ and $S_4$
capacitor $C_1$ charges, storing the initial energy $\frac{1}{2}LI_1{}^2$.
95 The reverse current $L_2 \neq I_1$ then flows through switch
$S_2$, L and switch $S_3$ with appropriate gating,
provided that the energy equivalent of $\frac{1}{2}Li_2{}^2$ was
previously stored on the capacitor $C_2$.

If the switching process is only seldomly
100 repeated, the necessary peak voltages on $C_1$ and $C_2$
may be ensured by adding two circuit arrangements
as described in Figure 3.

In order to present roughly constant loads to the
two power supplies, $V_1$ and $V_2$, each half of the
105 bridge, i.e. $S_1$, $S_3$ and $S_2$, $S_4$ can be shunted by
additional current switches from both $D_6$ and $D_9$ to
earth.

The circuits described are capable of producing a
variety of useful current waveforms. One example is
110 a trapezoidal like burst of equal amplitude positive
and negative currents with periods $\tau_1$ and $\tau_2$, see
Figure 5(a). A similar current waveform with
unequal positive and negative currents is shown in
Figure 5(b). Since the circuits actually switch off at a
115 zero-crossing, time delays $P_1$ and $P_2$ may be
interposed as indicated in Figure 5(c).

The trapezoidal edges in all cases are cosinusoidal
with a rise or fall time of $t_s$, which is experimentally
accessible. For rapid switching $t_s$ is short, but this
120 may be lengthened as in Figure 5(d). The circuit can
also be used to generate true sinusoidal waveforms,
Figure 5(e) or mixed sinusoids, Figure 5(f).

Arrangements for energy storage using
capacitors have been described above. This is
125 convenient since tuned circuits naturally
interconvert between magnetic and electrostatic
energy. In practice equations (8) and (9) dictate the
storage capacitance and the peak voltage.
Assuming the components can withstand this
130 voltage, there is still the problem of top-up provided

by the supply $V_2$ in Figure 1, and the initiating charge provided by $V_3$ in Figure 3. Both arrangements require relatively high voltage power supplies and in the case of $V_2$, the current drains can
5  be significant. For one shot waveforms there is no problem. But with repeating waveforms, as used in EPI, HT or even EHT power supplies may be required.

An attractive and alternative approach is to use
10  the capacitor C as a short term energy store, transferring the energy to another storage inductance, L′, placed well away from the primary coil L. A circuit arrangement is shown in Figure 6 using two bridges and two low voltage power
15  supplies $V_1$ and $V_1'$. If L = L′ then $V_1 = V_1'$. Losses in the system are made up by passing extra current through L′. The losses referred to arise from power dissipation in the diodes and switches. Long term losses in the inductance ($I^2r$) are made up from the
20  power supply. In a superconductive coil, these are zero. Thus once the current I is achieved in L or L′ the current would be maintained with no power consumption. Note that in this arrangement, capacitor C can be small. The rise time would be
25  limited purely by the voltage capabilities of the switches and diodes. The storage capacitor is required to hold charge for only a short time and no top-up voltage source or high voltage start-up supply is required.
30  Although a four element bridge for storage coil L′ strictly speaking, is not required, the arrangement of Figure 6 provides a more or less constant load for supply $V_1'$. As in the previous circuits, the bridge for coil L should be shunted with a third arm to provide
35  a current drain on $V_1$ when all four switch elements of that bridge are off.

An alternative circuit is shown in Figure 7. In this arrangement as in Figure 1 energy is momentarily stored in capacitor C when reversing the current
40  direction through L. However, when it is desired to switch off all four switches $S_1$ to $S_4$, the magnetic energy $\frac{1}{2}LI^2$ in coil L is first transferred to coil L′ via switch $S_9$. Current through $S_9$ is controlled by a current regulator CR. The current flow through coil
45  L′ and its energy $\frac{1}{2}L'I'^2$ in coil L is then maintained from the same supply V. A short time before current flow in coil L is required switch $S_9$ is opened and the energy in coil L′ is dumped into capacitor C thus providing the necessary initial condition for start-up.
50  This means that the current drain is fairly constant thus avoiding transient problems in the low voltage power supply. No HT or EHT top-up supplies are needed in this arrangement.

The various switches referred to can be
55  bidirectional mechanical devices, bidirectional solid-state devices, e.g. FET′s, standard high power transistors, SCR′s, unidirectional vacuum tubes or gas filled thyratrons. All can be made to function with appropriate driving circuitry. Naturally for high
60  speed operation, mechanical switches are not as useful.

A practical circuit based on Figure 1 is shown in Figure 8. Power FET′s (HEXFETS IRF130) are used as the switches $S_1$ to $S_5$, the integral body diode of
65  these devices being employed for the return current

paths.

A switching time $t_s$ of 50 μs was chosen in order to keep the peak capacitor voltage below the device limit of 100 V using equations (8) and (9). A
70  capacitor of 10 μF satisfies the requirements.

Switch $S_5$ is arranged to open between transitions after the current has settled (i.e. $2t_s$ after the last transition) to enable the capacitor voltage to be topped up to $V_2$ as described earlier and shown in
75  Figure 2(a). This switch closes during a transition, when energy is being transferred into C via $S_5$′s body diode or via $S_5$ itself when it has closed, and $S_5$ remains closed until the stored energy in C has been returned to the coil at time t = $2t_s$.
80  Each HEXFET has its own high speed opto-isolated gate drive circuit, the gate signals $G_1$ to $G_5$ are derived from TTL logic designed to supply the appropriate timings to the five gates.

In this arrangement there is no requirement for
85  instantaneous switching or simultaneous switching of any of the devices. Also, there is always a current path in circuit with coil L, either via the devices or the diodes during transitions thus minimising the possibility of 'glitches'.
90  Series/parallel combinations of devices can be used for higher voltages and currents and for shorter transition times.

The circuit of Figure 8 has been used to switch a current of 20 A through a coil L of 100 μH with a
95  switching time $t_s$ of 50 μs.

More powerful switches, e.g. SCR′s can be used to handle very high voltages and currents (~4 kV and 1000 Amps). Suitable snubber circuits may be introduced between the anodes and cathodes of the
100  SCR′s in order to prevent their retriggering.

CLAIMS

1. An inductive circuit arrangement comprising four switches connected in a bridge configuration,
105  current supply terminals to opposite ends of the bridge, inductive coil means connected across the bridge so that current can flow in either direction through the coil means depending on the setting of the switches, a series connection of capacitor means
110  and a switch connected across the supply terminals, and means for operating the said switches so as to connect the capacitor means across the coil means at least for a sufficient period of time until the current flow through the coil reduces to zero by
115  charging of the capacitor means.

2. The arrangement as claimed in Claim 1 in which the said switches are shunted by unidirectional current flow devices.

3. The arrangement as claimed in either one of the
120  preceding claims in which the said means for operating the switches functions subsequently to allow the capacitor means to discharge to generate current flow through the coil means in the opposite direction to the said current flow.
125  4. The arrangement as claimed in any one of the preceding claims in which there is provided trickle charge means connected to the capacitor means to enable the capacitor means to be charged to a predetermined voltage value after discharge.
130  5. The arrangement as claimed in Claim 4 in which

the said predetermined voltage is greater than the voltage across the supply terminals.

6. The arrangement as claimed in any one of the preceding claims in which a unidirectional current
5 flow device is connected in series with the current supply terminals to prevent flow of current through the current supply terminals in the reverse direction.

7. The arrangement as claimed in any one of the preceding claims in which initiating charge means is
10 connected through a switch to initially charge the capacitor means to a peak voltage to provide the requisite electrical energy to establish the required current flow in the said coil means.

8. The arrangement as claimed in any one of the
15 preceding claims in which there is provided a switched parallel path across the bridge to maintain a substantially constant value of current through the current supply terminals irrespective of the settings of the switches in the bridge configuration.
20 9. The arrangement as claimed in any one of the preceding claims in which the two arms of the bridge at one end thereof are connected to respective current supply terminals each at different voltage levels to enable different values of current
25 flow to be established through the coil means in respective opposite directions.

10. The arrangement as claimed in Claim 9 in which separate series connections each of a capacitor means and a switch are connected to said
30 respective current supply terminals.

11. The arrangement as claimed in any one of the preceding claims in which further coil means is provided together with further switch means to enable energy stored in said capacitor means to be
35 transferred to said further coil means.

12. The arrangement as claimed in Claim 11 in which said further switch means also enables energy stored in said further coil means to be transferred to said capacitor means.
40 13. The arrangement as claimed in Claim 12 in which the further switch means is connected in a bridge configuration and said further coil means is connected across the said further bridge configuration.
45 14. An inductive circuit arrangement substantially as described herein with reference to Figure 1 or Figure 1 as modified by Figure 3 of the accompanying drawings.

15. An inductive circuit arrangement substantially
50 as described herein with reference to Figure 4 or Figure 6 or Figure 7 or Figure 8 of the accompanying drawings.